

X-ray and γ -ray observations of millisecond pulsars

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ABSTRACT. The launch of several sensitive X-ray and γ -ray instruments during the last decade heralded a new era in the research of millisecond pulsars. The current number of millisecond pulsars detected in the X-ray spectral window is about 30, including those located in globular clusters, which represents a significant fraction of the total number of spin-down powered pulsars emitting high-energy radiation. In this paper the observational X/ γ -ray status is reported for a subset of X-ray emitting millisecond pulsars which show high-energy tails: PSR B1821-24, PSR J0218+4232 and PSR B1937+21. The prospects for future detection of these 3 millisecond pulsars at soft (INTEGRAL) and hard (AGILE/GLAST) γ -rays are discussed.

1. Introduction

Millisecond pulsars are rapidly spinning neutron stars with (very) small period derivatives ($P \lesssim 15$ ms; $\dot{P} \lesssim 10^{-17}$ s/s). Pulsars belonging to the millisecond-pulsar (MSP) group are preferentially located in binary systems (75%), commonly with a white dwarf companion. It is generally believed that these sources represent the final stage of low-mass X-ray binary evolution. The link between the X-ray binary and MSP stage is formed by the so-called accretion-driven X-ray MSPs of which there have been detected six members nowadays (Wijnands 2003). The first X-rays from a spin-down powered

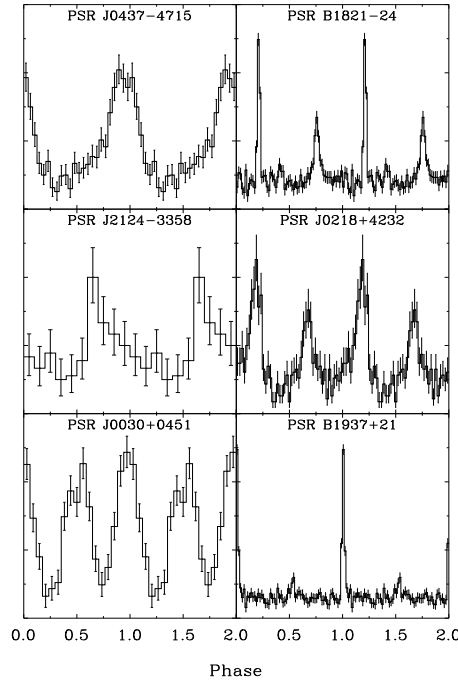


Fig. 1. X-ray pulse profiles for the six spin-down powered MSPs showing X-ray modulation at the rotational period. The pulsars in the left panels belong to the Class-I X-ray emitting MSPs characterized by low X-ray luminosities, soft spectra and broad pulses. In contrast, the right panels show the Class-II MSPs with high X-ray luminosities, hard spectra and narrow pulses.

MSP had been detected by Becker & Trümper (1993) for PSR J0437-4715. With this detection a new spectral window, besides the radio band, was opened in which MSPs can be studied. Currently, there are 12 plus 16 (the latter in globular cluster ⁴⁷Tuc;

Grindlay et al. 2003) X-ray emitting spin-down powered MSPs detected. Of these, six (probably one more; PSR J1012+5307) are known to emit *pulsed* X-ray emission. The X-ray pulse profiles for this small group composed of PSR J0437-4715, PSR J2124-3358, PSR J0030+0451, PSR B1821-24, PSR J0218+4232 and PSR B1937+21 are shown in Fig. 1. This small group can on observational X-ray characteristics be subdivided in two classes, Class-I and II (Kuiper et al. 2000).

The Class-I members - PSR J0437-4715, PSR J2124-3358 and PSR J0030+0451 - have low X-ray luminosities (1-10 keV; $< 10^{30}$ erg/s), soft predominantly thermal X-ray spectra (e.g. Halpern et al. (1996), Zavlin et al. (2002), Sakurai et al. (2001), Becker et al. (2002)) and broad pulses. It is generally believed that for this class the (modulated) X-ray emission originates from the polar cap region which is heated by backwards flowing particle currents in the pulsar's magnetosphere (thus thermal emission). Note, that in view of the high age of millisecond pulsars in general X-ray emission due to global surface cooling forms not a viable mechanism.

In contrast, the Class-II members - PSR B1821-24, PSR J0218+4232 and PSR B1937+21 - have high X-ray luminosities (1-10 keV; $> 10^{32}$ erg/s), hard power-law shaped X-ray spectra and emit narrow X-ray pulses. These characteristics point to a non-thermal origin related to physical processes taking place in the compact magnetosphere of a MSP. Because the latter class shows hard X-ray spectral tails up to ~ 20 keV and because for one member, PSR J0218+4232, pulsed high-energy γ -rays have been detected (Kuiper et al. (2000,2002)) the MSPs in this class are promising candidates to be detected at high-energy γ -rays (> 100 MeV) by the future γ -ray missions AGILE and GLAST and at soft γ -rays (15-1000 keV) by INTEGRAL, launched October 2002. Therefore, in the remainder of this review we will focus on the Class-II MSPs.

2. The Class-II X-ray millisecond pulsars

2.1. PSR B1821-24

The first MSP discovered in a globular cluster was PSR B1821-24 in M28/NGC 6626 (Lyne et al. 1987). It is a solitary pulsar with a pulse period of ~ 3.05 ms and a period derivative of 1.6×10^{-18} s/s. Its characteristic age of 3×10^7 year and spin-down luminosity of 2.2×10^{36} erg/s make it the “youngest” and most energetic MSP known today. Pulsed X-ray emission from this MSP was discovered by Saito et al. (1997) using ASCA GIS data (0.7-10 keV). Two narrow pulses with different intensities and separated ~ 0.55 in phase (phase distance between main X-ray pulse and secondary X-ray pulse) were visible in the pulse phase distribution. Also at soft X-rays (0.1-2.4 keV) the X-ray pulsations were detected (ROSAT HRI; Danner et al. 1997). The hard nature of the pulsed emission suggested a magnetospheric origin.

Inaccuracies in the ASCA and ROSAT clocks prevented an “absolute” alignment of the X-ray and radio profiles. A short 6.5 ks observation performed on 16 September 1996 with the PCA aboard RXTE made such a comparison in absolute phase possible (Rots et al. 1998): the X-ray (2-16 keV) and radio profiles were nearly aligned, the main X-ray pulse XP1 lags the radio pulse by $\sim 60\mu\text{s}$. It is interesting to note that the XP1 location is coincident with the phase location, where radio giant pulses occur (Romani & Johnston 2001). Subsequent long exposure RXTE observations (85.5 ks during 10 – 12 February 1997; 32.8 ks during 12 – 13 November 1999) of PSR B1821-24 made it possible to study the X-ray timing and spectral properties in detail (e.g. Kawai et al. 1999; Kuiper et al. 2004). The resulting high statistics X-ray pulse profile (2-20 keV) is shown in the upper right panel of Fig. 1. The phase separation is 0.546(2) and the FWHM's of the X-ray pulses are 0.018(1) and 0.046(6) for pulse 1 and 2, respectively, fitting two symmetric Lorentzians and a flat background to the X-ray pulse profile. This corresponds to very small pulse widths of $55\mu\text{s}$ and $140\mu\text{s}$ for pulse 1 and 2, respectively! Combining the data from the three RXTE observations and two ASCA observations a

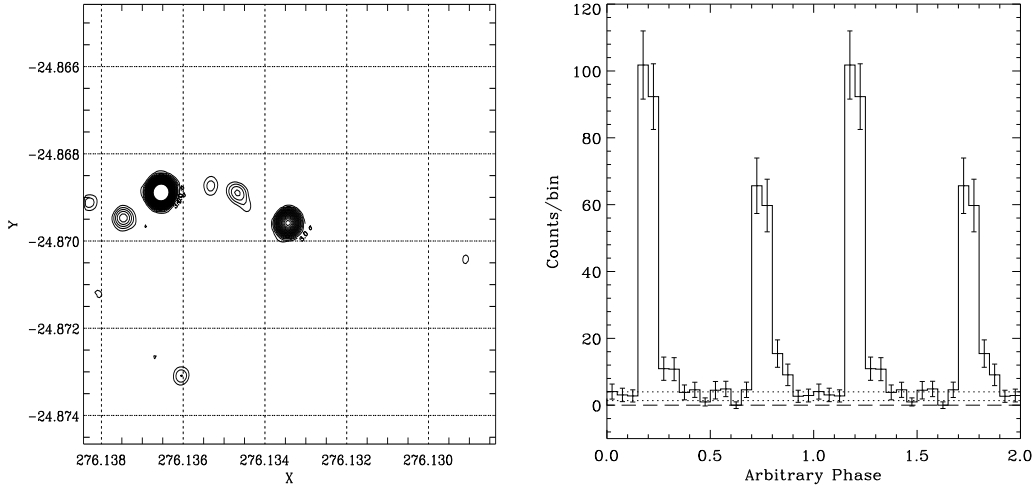


Fig. 2. (left) ML-image of the crowded core of M28 using HRC-SI data (0.08-10 keV). The fully resolved central point source is PSR B1821-24. The X and Y axes represent the RA-TAN and DEC-TAN for epoch 2000 in degrees. (right) Pulse profile of PSR B1821-24 obtained from a phase-resolved ML-imaging analysis adopting 20 phase slices. The dotted lines represent the $\pm 1\sigma$ uncertainty boundaries for the DC-emission ($12\% \pm 6\%$).

joint spectral analysis (0.8-20 keV) of the pulsed spectrum yielded a photon index of 1.13(2) assuming an absorbing column N_H of $1.6 \times 10^{21} \text{cm}^{-2}$ (Kuiper et al. 2004).

The location of PSR B1821-24 near the crowded core of globular cluster M28 requires high-resolution X-ray imaging to derive e.g the spectrum and pulsed fraction *not* polluted by contributions from neighbouring sources. Such high-resolution imaging observations have recently been performed with the Chandra ACIS-S and HRC-SI instruments. The total (pulsed plus DC) 0.5-8 keV spectrum obtained with the ACIS-S could be described by a power-law with photon index $1.20 \pm_{0.13}^{0.15}$ (Becker et al. 2003). Both the photon index and normalization of the total spectrum are consistent with the corresponding numbers for the pulsed component alone, leaving little room for a DC-component.

A 50.8 ks Chandra HRC-SI observation of PSR B1821-24 on 8 November 2002 made it possible to resolve the source and to determine the pulsed fraction of PSR B1821-24 for the integral 0.08-10 keV energy band. A value of 0.85 ± 0.03 was obtained (Rutledge et al. 2004). We derived an HRC-SI image from this observation using a Maximum Likelihood (ML) imaging method (Kuiper et al. 1998a) demonstrating the power of high-resolution imaging in crowded fields (see Fig. 2 (left panel)). The pulsed fraction (0.08-10 keV) obtained from a phase-resolved ML-imaging analysis is 0.88(7), consistent with the value obtained by Rutledge et al. (2004) using a different approach. The pulse profile resulting from the phase-resolved imaging study adopting 20 phase slices of equal width is shown in Fig. 2 (right panel). The $\pm 1\sigma$ uncertainty boundaries on the DC-emission are shown by dotted lines.

Finally, at soft and high-energy γ -rays only upper limits have been reported (CGRO OSSE: Schroeder et al. (1995) ; CGRO EGRET: Fierro et al. (1995)).

2.2. PSR J0218+4232

PSR J0218+4232 has been discovered by Navarro et al. (1995). It is a luminous radio pulsar with a pulse period of 2.3 ms orbiting a degenerate companion in ~ 2.0 days. Its radio profile is broad and complex with three pulses (Navarro et al. 1995; Stairs et al.

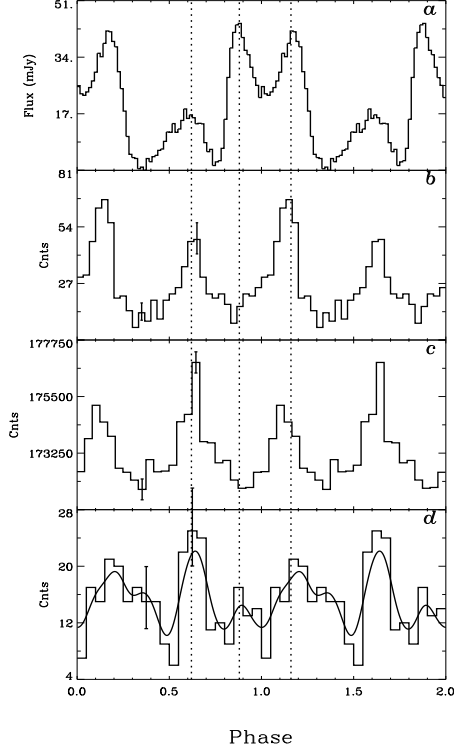


Fig. 3. Multi-wavelength pulse profiles of PSR J0218+4232 in absolute phase. From top to bottom: Radio 610 MHz, X-rays: Chandra HRC-SI 0.08-10 keV and RXTE PCA 2-16 keV, and high-energy γ -rays: CGRO EGRET 100-1000 MeV. Note the morphology change of the pulse profile at X-rays (panels b and c). The three dotted lines indicate the locations of the radio pulses, while the smooth curve superposed on the pulse phase distribution in the bottom panel represents the Kernel Density estimator (see Kuiper et al. 2002).

1999) and never goes off (DC radio component).

Soft X-ray emission (0.1-2.4 keV) from this source was detected by Verbunt et al. (1996) in a short ROSAT HRI observation performed in August 1995. Its pulsed nature was discovered by Kuiper et al. (1998b) in a 98 ks ROSAT HRI follow-up observation (July 1997). The 0.1-2.4 keV pulse profile showed two peaks separated in phase by 0.47(1). The pulsed fraction (0.1-2.4 keV) was $37 \pm 13\%$ indicating a large DC (non-pulsed) contribution. Spectral (phase-resolved) information at X-rays has been obtained by the MECS instrument (1.6-10 keV) aboard BeppoSAX. The major findings (Mineo et al. 2000) from this ~ 83 ks observation are: a) the total pulsed emission is (very) hard (photon-index 0.61 ± 0.32); b) the morphology of the X-ray profile changes as a function of energy; c) the DC-fraction is a function of energy and above ~ 4 keV it is consistent with being zero.

At high-energy γ -rays Kuiper et al. (2000) reported the likely detection of pulsed γ -ray emission from this pulsar using CGRO EGRET data. The source was seen in the map below 1 GeV and the two pulses visible in the 100-1000 MeV pulse profile (deviation from uniformity $\sim 3.5\sigma$) turn out to be aligned with two of the three radio pulses.

At X-rays the absolute timing accuracy for both the ROSAT HRI and BeppoSAX MECS did not allow to phase relate the radio and X-ray profiles. Two ~ 75 ks Chandra observations, one with the HRC-I and a second with the HRC-SI, made it possible to determine the phase alignment of the X-ray and radio profiles and to study the spatial extent of the X-ray emission from PSR J0218+4232 (Kuiper et al. 2002). The X-ray emission appeared to be point-like i.e. there were no indications for extended emission beyond $1''$ scales (diameter). The two non-thermal X-ray pulses in the 0.08-10 keV profile (see Fig. 1 middle right panel) are coincident with two of the three radio pulses *and* with the two γ -ray pulses, increasing the detection significance of the pulsed γ -ray signal to $\sim 4.9\sigma$. The pulsed fraction in the integral 0.08-10 keV band is 0.64 ± 0.06 . Combining

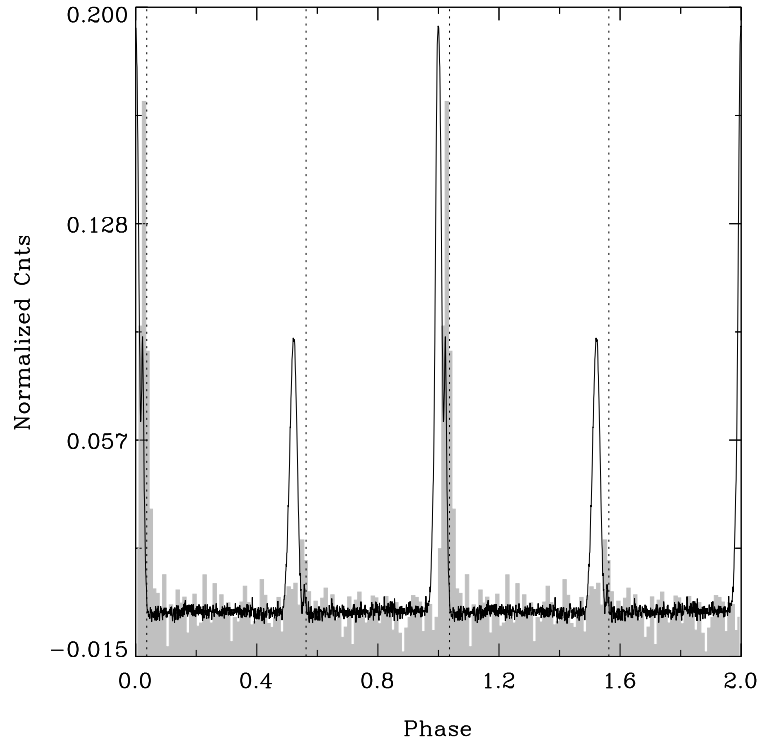


Fig. 4. RXTE PCA 2-10 keV pulse profile (histogram; light grey) with superposed a 1410 MHz radio profile obtained from Effelsberg observations in absolute phase. The X-ray main and secondary pulses lag the radio main and interpulse by $\sim 44\mu\text{s}$ and $\sim 51\mu\text{s}$, respectively. The X-ray pulse locations are coincident with the locations where the radio giant pulses are found (dotted lines).

the DC informations from the ROSAT HRI, BeppoSAX MECS and Chandra HRC-SI yielded, assuming a power-law shape model, a photon index in the range 1.3 – 1.85 for the non-pulsed emission. This is indeed considerably softer than the spectrum of the pulsed component.

RXTE observed PSR J0218+4232 for ~ 200 ks between 26-12-2001 and 7-1-2002. Pulsed X-ray emission was detected up to ~ 20 keV in both the RXTE PCA and RXTE HEXTE data (Kuiper et al. 2004). The X-ray pulse alignment relative to the radio profile verified the Chandra alignment results (see Fig. 3 for a multi-wavelength comparison of the pulse profile of PSR J0218+4232). A spectral analysis of the total pulsed signal combining (revisited) BeppoSAX MECS and RXTE PCA data yielded a photon-index of 0.99 ± 0.03 over the entire MECS/PCA energy range, one of the hardest spectra measured so far for any of the spin-down powered pulsars detected at X-rays!

Finally, it is interesting to note that recently also for this pulsar large amplitude pulses have been detected at radio frequencies (Joshi et al. 2004).

2.3. PSR B1937+21

PSR B1937+21 was the very first MSP discovered at radio frequencies (Backer et al. 1982). With its spin period of 1.56 ms this solitary MSP is still the most rapidly rotating neutron star currently known. A remarkable feature is the existence of giant radio pulses

(Wolszczan et al. 1984; Sallmen & Backer 1995; Cognard et al. 1996) similar to those of the Crab pulsar. An initial attempt to search for X-ray emission from this MSP was performed by Verbunt et al. (1996). They found no soft X-ray emission from the pulsar position in a ~ 24 ks ROSAT HRI observation. However, at harder X-rays (> 2 keV) Takahashi et al. (2001) found eventually X-ray pulsations in ASCA GIS data. One very narrow pulse was visible in the X-ray pulse profile with an indication for a weaker second pulse. This second weaker pulse was convincingly detected in a 78.5 ks BeppoSAX MECS observation (Nicastrò et al. 2002, 2004) performed in 2001. Spectral analyses of the total and pulsed signals (1.3-10 keV; MECS) showed a significant difference in the hardness of the spectra: total emission power-law index $1.94 \pm_{0.11}^{0.13}$; pulsed emission $1.21 \pm_{0.13}^{0.15}$. This is evidence for the presence of an underlying soft DC-component whose spatial extension is compatible with the MECS point spread function, and its contribution to the total emission amounts $\sim 45\%$ in the 1.3-4 keV band (Nicastrò et al. 2004).

In February 2002 PSR B1937+21 was observed by RXTE for about 140 ks. In the high-resolution PCA 2-10 keV pulse profile two (very) sharp pulses were visible separated 0.526(2) in phase (Cusumano et al. 2003). The X-ray main and secondary pulses lag the radio main and interpulse by just $\sim 44\mu\text{s}$ and $\sim 51\mu\text{s}$, respectively (see Fig. 4). Their locations are coincident with the locations where at radio frequencies giant radio pulses occur. At radio frequencies the phase separation between the normal main pulse and interpulse is 0.52106(3) (Kinkhabwala & Thorsett 2000), while the separation between the locations of the giant radio pulses amounts 0.5264(6). The latter value is more consistent with the pulse separation at X-rays. Pulsed X-ray emission was detected up to ~ 20 keV and its spectrum could satisfactorily be described by a power-law with index 1.14 ± 0.07 , consistent with the MECS derived value.

At soft and high-energy γ -rays only upper limits have been reported (CGRO OSSE: Schroeder et al. (1995) ; CGRO EGRET: Fierro et al. (1995)).

3. Discussion & conclusion

The Class-II MSPs discussed in this review exhibit (very) hard pulsed spectra at X-ray energies up to ~ 20 keV with photon indices in the range 1 – 1.2. Their spectra must soften drastically in the hard X-ray or soft γ -ray range in order to be consistent with the flux upper limits for PSR B1821-24 and PSR B1937+21 and the flux measurements of PSR J0218+4232 at γ -ray energies (see Fig. 6). Such kind of spectra is reminiscent to that of unidentified high-energy γ -ray sources (UGS; Grenier et al. (1997), Gehrels et al. (2000)) and therefore Class-II MSPs could explain at least part of the UGSs. At high-energy γ -rays AGILE and in particular GLAST can contribute significantly to the study of the high-energy properties of Class-II MSPs. Notably, the pulsed nature of the γ -ray emission of PSR J0218+4232 can be studied in more detail. At soft γ -ray energies long observations (> 1 Ms) with INTEGRAL IBIS ISGRI can yield important spectral information beyond 20 keV.

Models attempting to describe the high-energy emission from spin-down powered pulsars can crudely be divided in two classes: polar cap models (e.g. Harding et al. (1981), Daugherty et al. (1996)) and outer-gap models (e.g. Cheng et al. (1986,2000), Romani et al. (1996)). In polar cap models the high-energy radiation is produced close to the polar cap of the pulsar, while in outer gap models the high-energy radiation is generated in vacuum gaps near the last close field lines between the null charge surface and the light cylinder. At X-ray energies both model types predict a photon spectral index of ~ 1.5 (Rudak et al. (1999); Zhang et al. (2003)) which is too soft compared with the measured indices of the Class-II MSPs. Also, in the γ -ray regime such spectral discrepancies exist. This underlines the inability of the both classes of theoretical models to reproduce the emerging high-energy spectra for Class-II MSPs properly. In Kuiper et al. (2000) (see also Cognard et al. 1996, Saito et al. 1997, and Kuiper et al. 1998) it

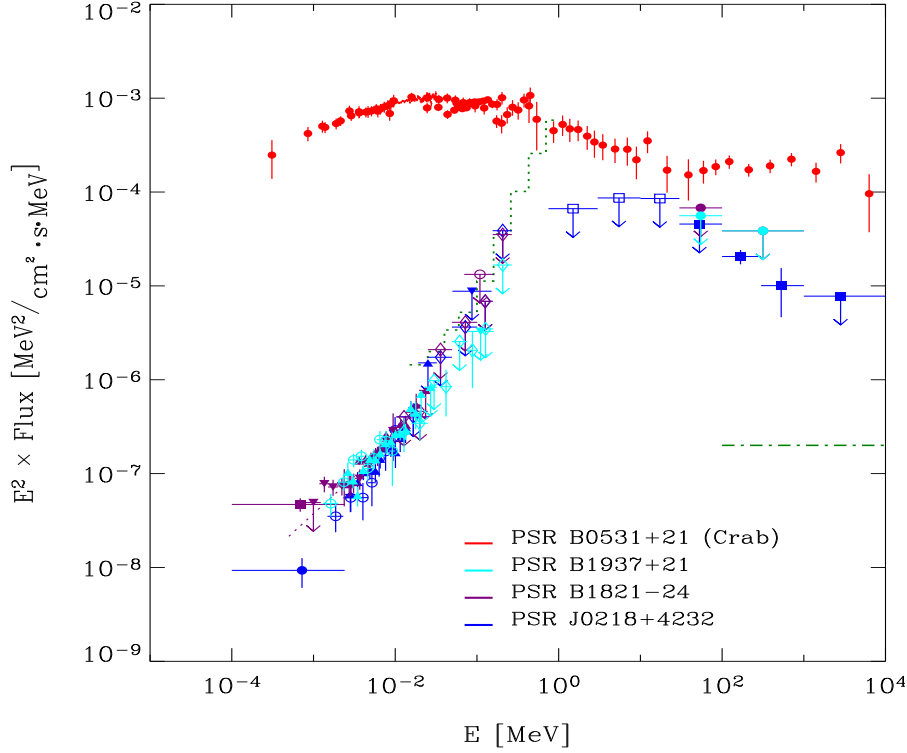


Fig. 5. Pulsed high-energy spectra of Class-II MSPs - PSR J1821-24, PSR J0218+4232 and PSR B1937+21 - in a νF_ν representation combining spectral information obtained by different X-ray and γ -ray instruments. The pulsed high-energy spectrum of the Crab pulsar is shown for reference. The 3σ sensitivity flux limits for the IBIS ISGRI detector aboard INTEGRAL assuming a 1 Ms observation are plotted as a dotted line. The dash-dotted line between 100-10000 MeV is the GLAST 3σ sensitivity limit. Notice the hard nature of the spectra at X-rays. The spectra soften dramatically at higher energies. The photon index for the γ -ray spectrum of PSR J0218+4232 is about 2.6. The overall spectral shape is reminiscent to that of unidentified high-energy γ -ray sources.

was noted that the three Class II MSPs together with the Crab pulsar and its twin in the LMC PSR B0540-69 are among the top six pulsars with the highest magnetic field strengths near the light cylinder (the sixth one is MSP PSR B1957+20). It was argued that the pulsed high-energy non-thermal emission of these pulsars originates quite likely in outer gaps near the light cylinder, based on similarities with the Crab pulsar. There is now additional supporting evidence in favour of an outer gap scenario for the production of the non-thermal emission: Giant/large amplitude radio pulses - a phenomenon likely related to the physical conditions near the light cylinder (Romani & Johnson 2001) - have now been detected for all Class II MSPs (PSR B1937+21, Cognard et al. 1996; PSR B1821-24, Romani & Johnson 2001; PSR J0218+4232, Joshi et al. 2003) as well as for the Crab (e.g. Lundgren et al. 1995) and very recently PSR B0540-69 (Johnston & Romani 2003). In fact, phase coincidences between radio giant and X-ray pulses have been reported by Romani and Johnson for PSR B1821-24 and by Cusumano et al. (2003) for PSR B1937+21. Future radio and high-energy observations of this intriguing class of MSPs are of great importance to shed light on the origin and nature of the emerging electro-magnetic radiation.

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